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Thoracoabdominal Aortic Aneurysm Repair: Interplay of Spinal Cord Protecting Modalities

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Background. *The purpose of this study was to assess the complementary use of different methods of measuring spinal cord perfusion during thoracoabdominal aortic surgery.*
Methods. *The spinal cords of 28 patients undergoing surgery on the thoracoabdominal aorta were monitored with transcranial electrical stimulation (tcMEP) and somatosensory-evoked potentials (SSEP). Available approaches of spinal cord-protection included: Moderate systemic hypothermia, constant cerebrospinal fluid (CSF) drainage and pressure monitoring, reimplantation of segmental arteries, cardiopulmonary bypass (CPB), and staged clamping.*
Results. *Fourteen of 19 patients (75%) undergoing open surgical treatment (Group I) exhibited loss of tcMEP after proximal aortic clamping. In nine cases (47%), we observed recovery of tcMEP after intraoperative interventions, while two patients subsequently developed paraplegia and three died. Seventeen of 19 patients showed loss of SSEP, with recovery in 12 cases (63%). During stent-graft implantation (Group II), one of nine patients (11%) demonstrated tcMEP loss with intraoperative, intervention-related recovery. The SSEP-recording course remained stable.*
Conclusions. *tcMEP/SSEP monitoring has proved to be an excellent means of detecting spinal cord ischaemia during surgery on thoracoabdominal aortic aneurysms. The prognostic value of tcMEP monitoring should be considered superior to that of SSEP measurements, because of its direct and rapid response to spinal malperfusion. Through combined neurophysiological monitoring, vital parameter balancing and intraoperative interventions, spinal cord perfusion improves and recovery of tcMEP and SSEP is achievable, reducing the prevalence of postoperative paraplegia.*

Keywords: Thoracoabdominal aortic aneurysm; Aortic surgery; Spinal cord perfusion; Spinal cord protecting modalities; Somatosensory-evoked potentials (SEP); Transcranial motor-evoked potentials (tcMEP).

Introduction

Spinal cord ischaemia can be considered the most serious complication of thoracoabdominal aortic aneurysm (TAAA) surgery. Due to its multifactorial aetiology, various spinal cord-preserving strategies have been expounded in order to improve clinical results. Three main factors contribute to spinal cord injury: Ischaemia during aortic cross-clamping, unsuccessful reattachment of spinal cord-perfusing arteries and cytotoxic damage caused by hypotension and reperfusion injury (delayed reperfusion injury).[1] A combination of complementary interventions protects the integrity of the spinal cord.[2–7] In this study, we assess the efficacy of monitored motor-evoked myogenic potentials after transcranial electrical stimulation (tcMEP) and somatosensory-evoked potentials (SSEP) as measures of spinal cord ischaemia[8–11] during endovascular stent-graft implantation and open surgery.

Material and Methods

Patient characteristics

Between November 2000 and March 2004, neurophysiological monitoring-assisted TAAA repair was carried out in 28 patients according to a standard surgical protocol. We divided our patients into two groups depending on the operation technique: Open surgical repair (Group I) was carried out in 19 patients and endoluminal repair in nine patients (Group II). No patient had any major neurological deficit prior to surgery. The median age of the nine female and 10 male patients in Group I was 56 years (range 29–81

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years). The main preoperative risk factors were hypertension (74%), hyperlipidaemia (42%), coronary artery disease (26%), chronic obstructive pulmonary disease (21%), and renal impairment (18%). The median age of the four female and five male patients in Group II was 65 years (range 53–81 years). The main preoperative risk factors were hypertension (100%), coronary artery disease (44%), renal impairment (44%), chronic obstructive pulmonary disease (22%), and diabetes (22%) (Table 1).

Neurophysiological monitoring technique

Transcranial motor-evoked potentials (tcMEP) are applied to observe the descending pathways. A motor reaction occurs in the peripheral regions by transcranial stimulation of the motor cortex. Somatosensory-evoked potentials (SSEP) are used to assess the ascending pathways. The EEG output following electrical stimulation of peripheral muscles is continuously measured. Both monitoring methods assess the central grey matter of the spinal cord and have a complementary controlling character: tcMEP recordings are sensitive to the anterior horn, SSEP recordings respond to the dorsal horn of the spinal cord. Using the 10–20 systems for EEG recordings tcMEP stimulation electrodes are attached percutaneously to the C3/C4 region of the motor cortex, SSEP recording electrodes are positioned at Cz/Fpz.[12,13] tcMEP recording sites on the leg are located at the tibialis anterior and gastrocnemius. SSEP stimulating electrodes are laterally and caudally anchored to the medial malleolus in order to excite the tibial nerve (EWACS and ISIS IOM; Inomed, Gesellschaft für interventionelle Medizintechnik mbH, Teningen, Germany).

The tcMEP stimulation impulse consists of a train of five anodal pulses of 200–400 μs duration, spaced by 2–4.5 ms (200–500 Hz). They are executed every 30–60 s by a constant current electrical stimulator (Digitimer DS7H; Digitimer Ltd, Welwyn Garden City, Hertfordshire, UK). Earthing occurs through a percutaneous needle electrode fixed between the stimulating and recording site (preferably in the knee region). The resulting electromyographic response does not require signal averaging. To change the stimulation side, we alter the polarity of the stimulus. The basic method to gain SSEP recordings is signal averaging due to the relatively long distance between the recording electrodes and the somatosensory cortex. The system registers the response of 200 consecutive stimuli as well as background noise, and filters the results in order to visualize and interpret the potentials.[14] After the patient has been anaesthetized, a baseline recording should be made. The baseline guarantees a correct definition of the patient's individual neurophysiological output. It is important to obtain the baseline recordings prior to surgery, as interferences from electrocautery usually preclude the making of viable recordings. The comparison between intraoperatively-gained potentials and the patient's individual baseline values enables the neurophysiological monitoring team to attain an assessment of actual spinal cord function.[15]

Postoperative continuation of neurophysiological monitoring during the 1st hours of ICU stay is an important tool to register delayed changes. It is worth noting that electrical stimulation is painful and cannot

Table 1. Patient characteristics

	Open surgery group (Group I)	Stent graft group (Group II)
Mean age (range) in years	56 (29–81)	65 (53–81)
Sex ratio (male/female)	10/9	5/4
Preoperative variables		
Arterial hypertension	14 (74%)	9 (100%)
Chronic obstructive pulmonary disease (COPD)	4 (21%)	2 (22%)
Coronary artery disease*	5 (26%)	4 (44%)
Diabetes	1 (5%)	2 (22%)
Renal impairment†	3 (16%)	4 (44%)
Hyperlipidaemia	8 (42%)	4 (44%)
Smoking	6 (32%)	0
Aneurysm aetiology and Crawford extent type		
Degenerative aortic disease	11 (58%)	6 (66%)
Chronic dissection	8 (42%)	3 (33%)
Type I	5 (26%)	3 (33%)
Type II	8 (42%)	6 (66%)
Type III	5 (26%)	0
Type IV	1 (5%)	0

* Criteria for coronary artery disease: Stenosis of the coronary arteries >50%, stenosis haemodynamically effective.
† Criteria for renal impairment: Serum creatinine >1.4 mg/dl.

be used in postoperatively awake, sedated patients. The extended control enhances the patient's security, especially after intraoperative loss of SSEP/tcMEP and the assumed spinal cord ischaemia, paraplegia or paraparesis.[16]

Surgical and anaesthesia technique

The night before surgery, all 28 patients underwent lumbar drainage to monitor and regulate CSF-pressure followed by routine monitoring until the 3rd postoperative day. The patients treated with open surgical repair of thoracoabdominal aortic aneurysms (Group I) were placed on the operating table in the right lateral decubitus position. Access was achieved via the Crawford approach.[17] A standard posterolateral thoracotomy with a fifth or sixth rib interspace incision provides adequate exposure of all types of aneurysms. In general, a double-lumen tube is necessary to deflate the left lung. The costal margin is divided, followed by a circumferential division of the left hemidiaphragm through its muscular portion, with a few centimetres left to re-attach the diaphragm to the chest wall. The abdominal portion of the incision is retroperitoneal. The Crawford approach is used for all types of aortic aneurysms (I–IV) with small adaptations according to their particular extent (Table 2).

Simultaneously, the right common femoral artery is dissected. Distal perfusion with femoro-femoral bypass is installed. Patients undergo systemic heparinization (300–400 IU/kg). After exposure of the aorta, staged cross-clamping is performed. The entire clamping system is gradually shifted proximally then distally, replacing the aneurysmal aorta with a prosthesis (Fig. 1). In order to ensure adequate perfusion of the spinal cord, visceral organs, and lower extremities, a distal perfusion pressure over 60 mmHg is compulsory. Having reached the abdominal aorta, selective perfusion with cooled blood (15 °C) of the coeliac axis, renal arteries, and superior mesenteric artery is accomplished. Dacron tube grafts (Sulzer Vascutek Ltd, Inchinnan, Renfrewshire, Scotland, UK) are anastomosed using running 4–0 prolene sutures (Ethicon Inc., Somerville, NJ, USA). We are guided by the neurophysiological monitoring team while reattaching the segmental arteries to the tube graft. As long as we can identify stable tcMEP and SSEP potentials after oversewing the segmental arteries, we deduce that these vessels are not crucial to the spinal cord blood supply and thus neglect them in the further course of the operation. In case of alterations in potential (i.e. extended latency and shortened amplitude), segmental artery preservation is desirable.

Those patients treated with endovascular stent-graft implantation (Group II) are placed on their backs. After exposing the femoral artery and correctly positioning the stent-graft device, the self-expanding endoprosthesis is deployed in the aneurysmal region of the thoracoabdominal aorta. Angiography is used for guidance and confirmation of the stent-graft position, excluding endoleaks and dislocation.

Close collaboration between the neurophysiologist and anaesthetist during TAAA repair is of vital importance, as complete neuromuscular blockade conflicts with tcMEP monitoring. Therefore, short-term muscle relaxants are applied only once at the beginning of general anaesthesia. Benzodiazepine (0.01–0.03 mg/kg) is given for sedation, and fentanyl (0.004–0.007 mg/kg) administered as an analgesic.

Spinal cord-protecting modalities

A group of strategic interventions are advantageous in preventing intraoperative and postoperative paraplegia after TAAA repair. The measures include monitoring vital parameters (being immediately and

Table 2. General differences in open surgery technique depending upon the Crawford classification

Crawford classification type	Aortic replacement	Reimplantation of arteries	Risk of paraplegia
I	Proximal: Upper descending thoracic aorta Distal: Visceral aortic segment	SA: All in area T8–T12 in case of potential alteration VRA: Either in distal anastomosis or in oblique prosthesis	↑↑
II	Proximal: See type I Distal: Aortic bifurcation	SA: See type I VRA: Single inclusion button	↑↑↑↑
III	Proximal: Middle descending thoracic aorta Distal: See type II	SA: See type II VRA: See type II	↑↑↑
IV	Proximal: Transition thoracic/abdominal aorta Distal: See type III	SA: None VRA: See type III	↑

SA, segmental arteries; VRA, visceral and renal arteries.

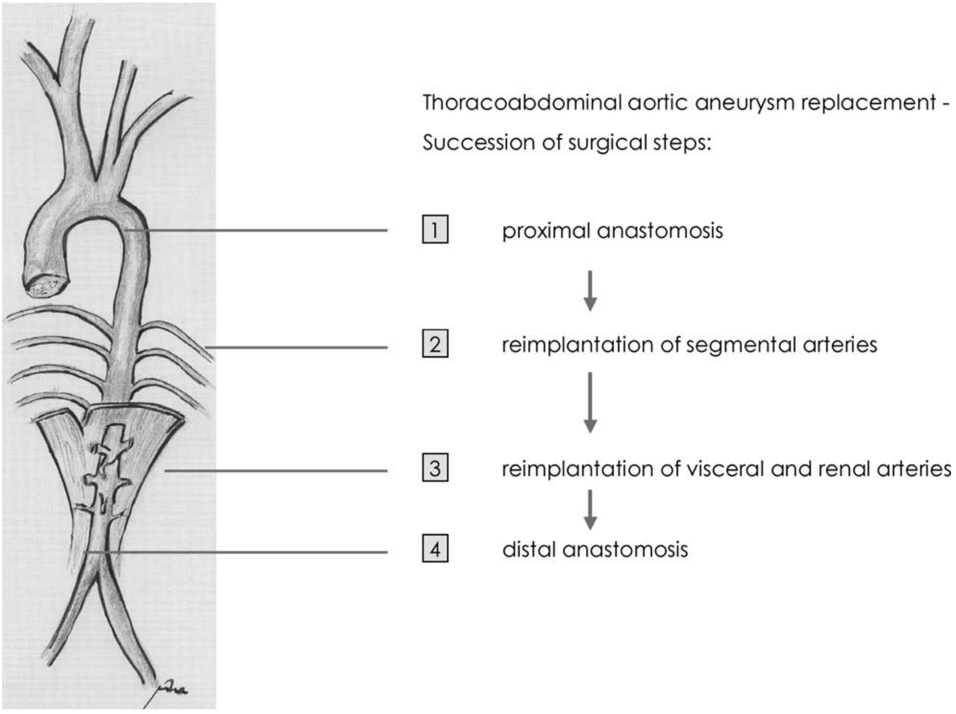

Fig. 1. Surgical technique for open repair: Step-by-step replacement of the aneurysmatic aorta.

individually adjustable) and evoked potentials (triggering surgical interventions) on the one hand and solely surgical steps securing sufficient spinal cord perfusion on the other hand (Fig. 2). This individually applied triad lays the foundations for the optimum up-to-date spinal cord protection results.

One basic step to safeguard spinal cord and visceral organ circulation against disadvantageous defects is the constant adjustment of mean aortic pressure (MAP) parameters (60 mmHg). A drop in MAP below the desired average of 60 mmHg is alleviated by use of volume replacement and inotropes. Nitroglycerine assists in regulating central venous pressure (CVP) at its standard level of ≤12 mmHg. The last step entails the level-balancing of CSF pressure below 20 mmHg.[18,19] Neurophysiological monitoring techniques are employed that elicit further surgical actions after changes in potential recordings have been noted. The reimplantation of segmental arteries critical to spinal cord perfusion is attempted while all other arteries of negligible relevance are—for time saving reasons—ignored and not reattached to the prosthesis. Proximal-to-distal staged clamping of the aorta permits adequate circulation in blood vessels not immediately adjacent to the surgical focus in question. According to the operative stage, some key arteries (renal arteries, coeliac axis and superior mesenteric artery, segmental arteries) are perfused with cooled blood (15 °C). Moderate systemic hypothermia (30–33 °C) is obligatory.[20–22]

Results

We performed TAAA repair in 28 patients. Nineteen patients underwent open surgical treatment (Group I = 68%), nine received a stent-graft implantation (Group II = 32%). Group I patients were documented as follows: Stable tcMEP potentials were reproducible in five of 19 patients (25%). None of them displayed neurological deficits after postoperative awakening. Bilateral tcMEP loss occurred in 14 of 19 patients (75%). Nine of them recovered after intraoperative spinal cord-protecting interventions, with no neurological deficits. In those cases, however, regained tcMEP recordings were usually smaller in amplitude and longer in latency. Complications emerged in five patients, two of whom died intraoperatively and one during the 1st hours in the ICU from low out-put syndrome. The remaining two patients suffered paraplegia. Stable SSEP potentials were reproducible in two of 19 patients (11%), SSEP loss occurred in 17 patients (89%). We regained SSEP recordings from intraoperative interventions in eight of 17 patients (47%). One SSEP characteristic is a prolonged response both in reaction to and recovery from spinal cord

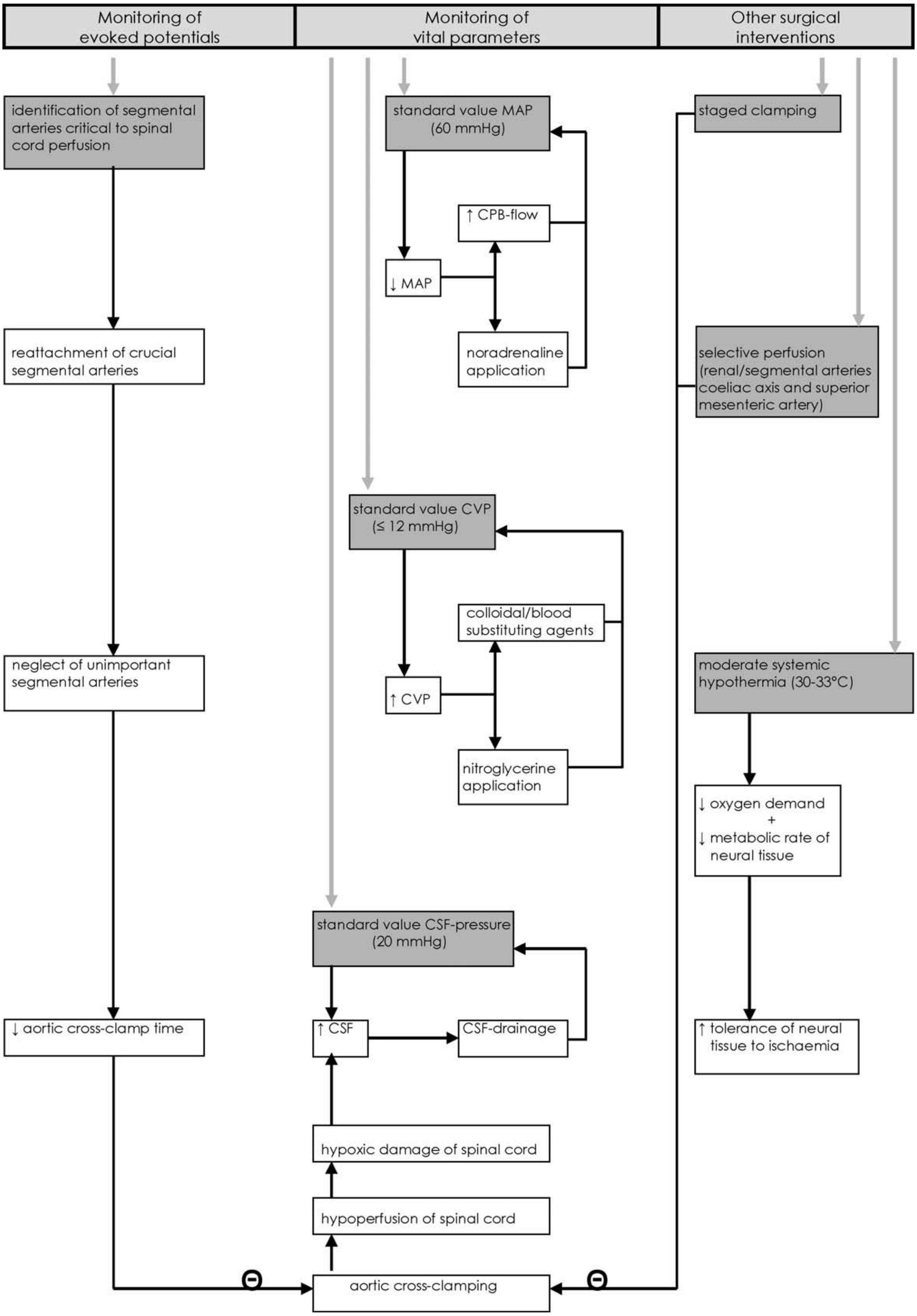

Fig. 2. Interplay of spinal cord protecting modalities. The main determining factors are highlighted with grey shades. MAP, mean aortic pressure; CPB, cardiopulmonary bypass; CVP, central venous pressure; CSF, cerebrospinal fluid; ↑, increase; ↓, decrease; Θ, obstructive influence.

Table 3. Open surgery repair (Group I): Intraoperative surgical data

Crawford classification type	I	II	III	IV
Changes of potentials	3	8	3	0
Recovery of potentials	2 (66%)	5 (63%)	2 (66%)	0
No recovery	1 (33%)	3 (37%)	1 (33%)	0
Aortic x-clamp (min)				
Mean	81	113	111	194
Range	52–125	42–202	41–210	
Segmental arteries (T8–T12)				
Identified (mean)	4.1	4.5	1.6	0
Reattached (mean)	1.8	1.75	1.2	0
Paraplegia	0	2	0	0
Death	1	2	0	0

ischaemia. In this context, continued monitoring during ICU stay proved wise, as we detected gradually regained potential in four patients. The five patients mentioned above with irreversible tcMEP loss also suffered from irreproducible SSEP potentials.

The aortic cross-clamp time varied according to Crawford classification type between 42 and 210 min (Table 3). Those patients with paraplegic or fatal complications had an extremely long x-clamp time compared to the mean value (Table 4). On average, we were able to identify 1.6–4.5 segmental arteries in segment T8–T12 of the Crawford types I–III. Only 1.2–1.8 (mean) intercostal arteries were re-attachable to the prosthesis due to atherosclerotic thoracoabdominal aneurysms combined with pathological deterioration of the tissue layer. Although numerous patent segmental arteries could be identified in three type II-patients, none of the vessels could be reimplanted due to the severely diseased aorta. No segmental arteries could be identified in three type II-patients with a history of chronic dissection.

The data on Group II patients is as follows: We recorded stable tcMEP in eight of nine patients (89%) with stent-graft implantation. One patient (11%) showed intraoperative tcMEP loss with subsequent, intervention-related recovery and no postoperative neurological deficit. The SSEP recording course remained stable in all Group II patients.

Discussion

Our results emphasize the clinical advantages of tcMEP/SSEP monitoring during thoracoabdominal aortic aneurysm (TAAA) repair. Nevertheless, a single, direct procedure for recognizing malperfusion has not been established. Therefore, paraplegia can only be prevented by combining neurophysiological procedures and intraoperatively vital parameter control plus direct surgical steps. Monitoring the neurophysiological functions of a patient undergoing TAAA repair is an ideal method to detect injuries or changes in spinal cord perfusion during surgery.

Simultaneous recording of neurological stimuli supports and influences the surgical method significantly. A distinction between the prognostic values of tcMEP loss *versus* SSEP loss can be made. SSEP potentials gradually deteriorate, combined with a retarded restoration and an impending long-term loss even after intervention. tcMEP potentials make interpretation of spinal cord function possible within several minutes after intervention, and they regenerate within a short time after loss of potential. Both types of evoked potentials gauge different anatomical spinal cord structures. SSEP measurements document the activity of the posterior and lateral columns of the spinal cord, while tcMEP assesses the corticospinal system. Despite their complementary nature, the prognostic value of tcMEP monitoring must be considered superior to SSEP measurements because

Table 4. Context of x-clamp time with identification and reattachment of segmental arteries in the five paraplegic/deceased patients

CCT	x-Clamp	SA identified	SA reattached	Result
II	134 min	1	1	Paraplegia
II	175 min	2	2	
II	125 min	5	0	Death
II	141 min	4	0	
I	202 min	4	0	

CCT, Crawford classification type; SA, segmental arteries.

of the former's direct and rapid response to spinal malperfusion.[23] The dorsal horn monitored by SSEP is less sensitive to hypoxia than are the alpha motoneurons. Simultaneous monitoring of tcMEP and SSEP causes frequent false-positive and false-negative monitoring results.[24]

Concerning the open surgery group, neurophysiological monitoring serves as a control mechanism to identify the point at which operative measures cause malfunctions within the patient's nervous system. Corrective steps to prevent or reduce the extent of paraplegia and paraparesis can be taken with little delay.[25] The instant reimplantation of segmental arteries crucial to spinal cord perfusion after changes in tcMEP/SSEP recordings was demonstrated to be important. However, the segmental artery anatomy in type II-patients with atherosclerotic aneurysms or a history of chronic dissection is damaged. In such cases, only few patent segmental arteries are appropriate for reattachment. Recovery of short-term deterioration of evoked potentials occurred in 63% after calculated intraoperative steps. This fact highlights the variability of the functional anatomy in patients with degenerative aortic structures and the importance of collateral spinal cord circulation.[26] Intraoperative interventions, such as an increase in distal perfusion, are particularly advisable.

In addition to neurophysiological monitoring-assisted surgical interventions, the adjustment of physiological parameters is important. Prompt reaction to easily-applied methods (MAP, CSF, CVP-regulation) makes quick and uncomplicated control possible. Staged clamping reduces the side effect of aortic cross-clamping. Selective perfusion serves to improve splanchnic, renal, and spinal cord oxygenation. Moderate systemic hypothermia decreases oxygen demand and the metabolic rate of neural tissue, thus increasing its tolerance for ischaemia.[16]

The endovascular stent-graft group reveals some main differences concerning paraplegia and evoked potentials. One distinguishing feature of stent grafting is its limited influence on the patient's physiology. None of our stent graft patients developed paraplegia, due to the advantages of this operation technique.[27] Aortic cross-clamping and therefore proximal hypertension with its negative side effects on cerebrospinal perfusion is unnecessary. Distal aortic perfusion remains uninterrupted, guaranteeing a continuous blood flow. Reperfusion damage is impossible as no reimplantation of segmental arteries occurs.

The clear advantages of stent graft-supported interventions result in a low incidence of changes in evoked potentials. Consequently, stent graft implantation is preferable to open TAAA-repair, as it lowers the rate of paraplegia and mortality.[28–30] However, endoluminal grafting does restrict the opportunity to manoeuvre in the case of impending loss of potential. The only option is to convert to open surgery, i.e. stent explantation and implantation of a prosthesis with consecutive reimplantation of all critical segmental arteries. In this instance, the inguinal stent graft access serves as a tool for swift femoro-femoral cannulation as well as cardiopulmonary bypass with cooled blood.

Despite a heterogeneous patient pool, we believe that this intraoperative monitoring approach in combination with a set of interventions creates the best possible outcome for thoracoabdominal aneurysm repair.

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